Small Spacecraft Overview

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Summary

Small spacecraft play a major role in earth, lunar, planetary, stellar, and interstellar discoveries. As technologies improve, instruments scale down in size, and their advantages in reduced cost and development time continue to attract investment, small satellites[1] will play an even more important role. Today, the growth rate of small spacecraft utilization is limited by the availability of affordable launch opportunities.

Introduction

Small spacecraft have been an integral part of space study, exploration, and commercialization since humankind's first steps into low Earth orbit with Sputnik-1 and Explorer-1. As defined in Table 1,

Spacecraft Class Definition		Wet Mass, kg	
Large Spacecraft		≥1000	
Small Spacecraft	Medium Spacecraft	500-1000	
	Mini Spacecraft	100-500 *	
	Micro Spacecraft	10-100	} Cubesats
	Nano Spacecraft	1-10	
	Pico Spacecraft	0.01-1	
	Femto Spacecraft	0.01-0.01*	

* organization-dependent upper thresholds vary from 180 to 500 kg
** organization-dependent upper thresholds vary from 0.01 to 0.1kg

Table 1 Spacecraft classification based on wet mass

"small spacecraft" are considered to be those with wet masses below 500kg. Although the 500 to 1000 kg mass range is defined technically as a "medium" spacecraft class, it is common to omit reference to medium classifications and refer to a spacecraft as either "small" or "large".

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[1] The term "satellite", commonly used in describing an artificial object in orbit around the earth or other celestial body, can also refer to a spacecraft on an escape trajectory to eventually exit our solar system.

Development of small satellite platform standards have created new opportunities in the nanosatellite market. The standard "one unit" (1U) cubesat spacecraft, illustrated in Figure 1, is a cube 10 cm on each side with a mass of approximately 1 kg. (CubeSat Program, 2014). Cubesats can be composed of a single cube (a "1U" cubesat) or several cubes combined forming, for instance, 3U, 6U or even 27U integrated units. Representative configurations and sizes are compared in Figure 2.

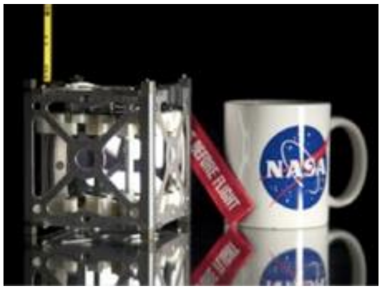


Figure 1 Typical 1U Cubesat

Most Cubesat masses qualify them as nanosatellites; however, cubesats less than 1 kg may be considered pico spacecraft. Practical femtosats have not yet entered the marketplace, but attempts to develop and launch such "ChipSats" systems are underway. (Jones, 2016)

Figure 2 Comparative size of 1U, 3U, and 6U Cubesats

Although their mass and volume constraints can significantly limit power, propulsion, and communication subsystem sizes, small spacecraft do provide certain advantages. With generally lower complexity and fewer payloads, small satellites can be produced at an increased cadence than larger ones. Rapid development provides organizations with more agility in meeting requirements and adapting to new technologies. For instance, the Department of Defense Operationally Responsive Space (ORS) program pursues small satellites to meet its primary goal to *rapidly* assemble, test, and launch satellites in support of warfighters. Rapid development can also drive costs down such that use of small satellites may allow more frequent research missions and technology demonstrations. Low cost developments can also provide opportunities for engineering and project management education and capability maturation. Cubesats, in particular, are often used as educational and technology demonstration platforms.

History and Evolution of Small Spacecraft

Small spacecraft are not a new phenomenon but rather are the original class of space vehicle and a cornerstone of the United States space program. The first artificial satellites – the Soviet Union's Sputnik 1 and The United States' Explorer 1 – were small satellites. More than 50 small spacecraft followed as part of NASA's Explorer Program – missions investigating earth science, astronomy and heliophysics. (NASA, 2017). Though small in size, complexity, and cost, NASA's Explorer spacecraft were well-engineered and highly reliable. Many continued to operate for 5 or more years; the longest-lived, IMP-8, operated for 33 years. (NASA, 2017)

Small spacecraft missions were not limited to just the Explorer Program. Many of the early interplanetary Mariner and Pioneer spacecraft may be categorized as small spacecraft. NASA's Apollo Program deployed two small lunar satellites as part of the Apollo 15 and 16 missions of the early 1970's. Organizations outside of NASA, including the Department of Defense, academia, and foreign governments, successfully developed and operated small spacecraft as well.

NASA began the Small Explorer Program (SMEX), in 1989 as a follow-on to the Explorer Program. Cost capped at $120M (FY17 dollars), with a primary goal of utilizing small spacecraft to conduct mission in astrophysics, space physics and upper atmospheric science, the SMEX program was also to usher in a new generation of engineers through apprenticeship with experienced spacecraft developers. A decade later, NASA initiated the University-class explorer ("UNEX") program to conduct missions at a per mission cost of less than $15M (FY17 dollars) that provides even more "hands-on" training ground for future spacecraft developers. Figure 3 shows the growing variety of NASA's small spacecraft over many decades.

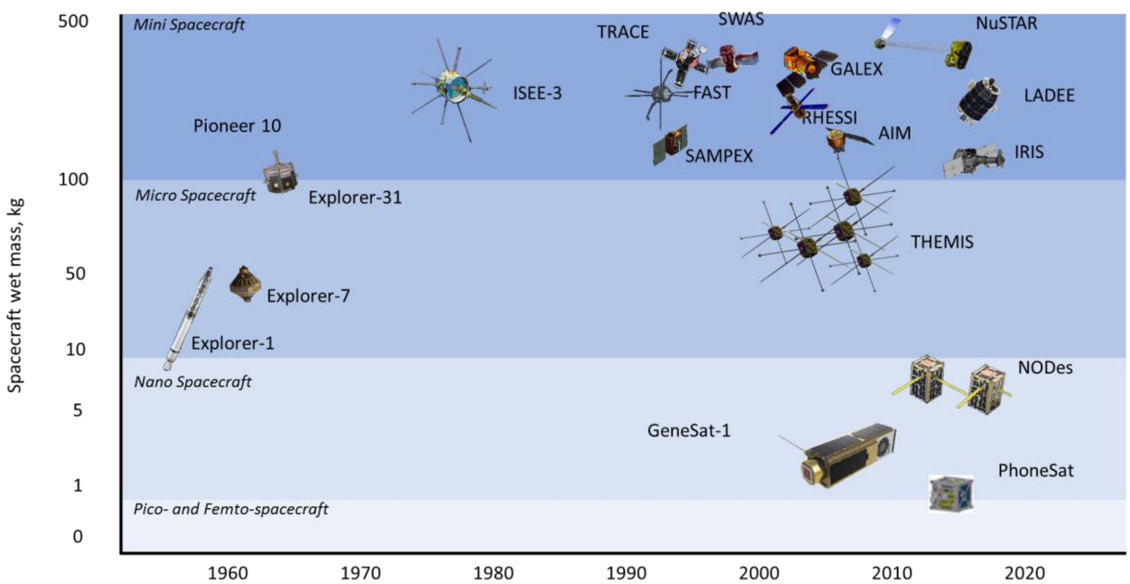


Figure 3 Small spacecraft mass trends over the past six decades

There are many examples of smallsats that provide cost-effective platforms for astrophysics, heliophysics, and Earth science research. One is the 200 kg Interface Region Imaging Spectrograph (IRIS) spacecraft that provides important insights into our Sun. Another is the 385 kg Stardust mission, launched in 1999, that collected comet dust samples and returned those samples to Earth. The Cyclone Global Navigation Satellite System (CYGNSS), launched in 2016, placed 8 microsatellites in low Earth orbit to study the formation and intensity of tropical cyclones and hurricanes. (NASA, 2016) The Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission launched a constellation of 5 smallsats to study Earth's magnetosphere. Military and commercial interest in smallsats has grown as well. In 2005, the 100 kg U.S. Air Force XSS-11 spacecraft demonstrated the ability to rendezvous with and repair another satellite. (David, 2005).

In 1999, the cubesat standard revolutionized the secondary payload industry, replacing non-functional "ballast mass" with small, low cost spacecraft and creating a new, diverse community of spacecraft developers. Cubesats provide low-cost access to space, enabling research and educational projects that might not otherwise be possible using “traditional” methods. Their low cost make cubesat educational programs accessible from the elementary school to university levels. Cubesat design, launch, and operation programs are a growing part of STEM curricula in K-12 schools, community colleges, and universities.

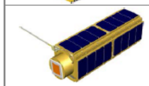
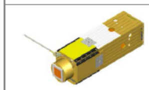
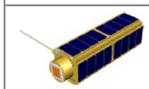
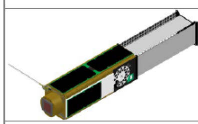
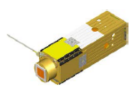
A cubesat dispenser design, the Poly-Picosat On-Orbit Deployer (P-POD) shown in Figure 4, emerged in parallel with the cubesat standard to enable easy integration with existing launch vehicles. The mechanically robust dispenser accommodated a pack of 3 1U spacecraft until commanded to eject the cubesats with a spring-actuated “foot”. Today, multiple cubesat dispenser options are available as open design standards and proprietary commercial solutions.

Figure 4 P-POD Cubesat Launcher

Beyond educational access to space, cubesats provide a low-cost, yet effective, means to demonstrate new technologies. For example, in 2012, NASA’s PhoneSat spacecraft demonstrated the application of COTS technologies for affordable spacecraft. NASA has also utilized cubesats for space biology experimentation since 2006. The U.S. Army’s Operational Nanosatellite Effect (ONE) program began investigating the use of cubesat platforms in 2011 (Brinton, 2011). Cubesats may also begin to play support roles in larger missions, for example, NASA’s InSight mission to Mars will use two Mars Cube One (MarCO) spacecraft to provide communications relay functions during InSight’s entry, descent and landing. (Matousek, 2014)

Low cost Earth imaging is an emerging commercial market that benefits from small satellite capabilities. Several new companies plan to leverage the simplicity, modularity and affordability of cubesats to create satellite constellations. (Bandyopadhyay, Subramanian, Foust, Morgan, & Chu, 2015) One such constellation already includes over 100 operating 3U cubesats. From low Earth orbit, these satellites may provide Earth imaging at the maximum resolution allowed under U.S. export law.

Government cubesat mission costs vary from $3 to $30 million and are typically determined by the scope of scientific capability, complexity, propulsion, control system type, and radiation tolerance requirements. A summary of selected NASA cubesat missions is provided in Table 2.

Spacecraft & Platforms	*Mission*	*Facts*	*Launch Date*	*Launch Vehicle*	*Status*
	*GeneBox*	➢ First NanoSat to integrate a 1U Bus to a 2U Payload ➢ First NanoSat to integrate onto the first privately launch Prototype Space Station (Genesis1) ➢ First NanoSat Fluidic / Optical Contained Payload System	July 12 2006 Yasny Launch Base	Dnepr	In Orbit Successful Mission
	*GeneSat 1*	➢ First NanoSat to integrate onto a Minotaur 1 ➢ First Biological Payload in a 3U NanoSat configuration ➢ First to fly a Microhard Radio ➢ First University Run Mission Ops for a NASA NanoSat	December 16 2006 Wallops Island, VA	Minotaur 1	Re-entered Summer 2010 Successful Mission.
	*PreSat*	➢ First NanoSat with a Biological Payload to integrate onto a Falcon 1 ➢ First Ames mission integrating two NanoSat spacecraft at once	June 21 2008 Kwajalein Atoll	Falcon 1	Prototype Unit Launch Vehicle did not reach Orbit
	*NanoSail-D 1*	➢ First NanoSat Solar Sail to integrate onto a Falcon 1 ➢ First NanoSat joint effort by AMES and MSFC ➢ First NanoSat to be viewed from the ground	June 21 2008 Kwajalein Atoll	Falcon 1	Launch Vehicle did not reach Orbit
	*PharmaSat 1*	➢ First PI lead Science Mission in a 3U NanoSat configuration ➢ First peer-reviewed publication from a NanoSatellite ➢ First Pharmaceutical Experiment ➢ First NASA Ames full science mission in a 3U NanoSat	May 19 2009 Wallops Island, VA	Minotaur 1	Re-entered 2012 Successful Mission
	*O/OREOS*	➢ First NanoSat to integrate onto a Minotaur 4 ➢ First 3U NanoSat to have 2 payloads running 3 experiments over a 6 month period ➢ First 3U NanoSat to integrate De-orbit Mechanism ➢ First University Run Mission Ops to track 2 NanoSats simultaneously	November 19 2010 Kodiak AK	Minotaur 4	Prototype Unit In Orbit Successful Mission In use for training by SCU
	*NanoSail-D 2*	➢ First 3U NanoSat to be deployed from a primary satellite ➢ First Solar Sail to be deployed and used as a De-orbit Mechanism ➢ First NanoSat to be optically tracked from the ground	November 19 2010 Kodiak AK	Minotaur 4	Re-entered Fall 2011

7/20/2015

Table 2 Example NASA Cubesat missions

Figure 5 illustrates the quickly growing number and diversity of missions utilizing nano and micro satellites. Earth observation and science areas have grown significantly since 2013. Overall, the number of cubesat launches have seen large increases, as shown in Figure 6. The rate has remained high since 2013—a record 103 small satellites were launched simultaneously on an Indian Polar Satellite Launch Vehicle in Feb. 2017. The increased cubesat launch rate reflects the expanding viability of these platforms for research and commercial activities, aided in part by the availability of commercially-produced standard small spacecraft buses. Projections suggest a total launch demand of about 2,400 satellites weighing 1 to 50 kg over the next five years. (Spaceworks Enterprises, Inc, 2017) Recent reductions in this five year projection may be the result of prolonged launch delays and a growing backlog of small satellite missions yet to launch.

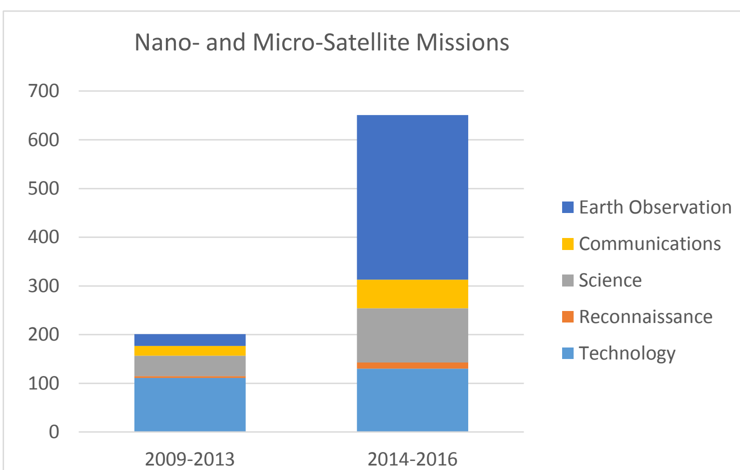


Figure 5 Increasing volume of nano- and micro-satellite missions

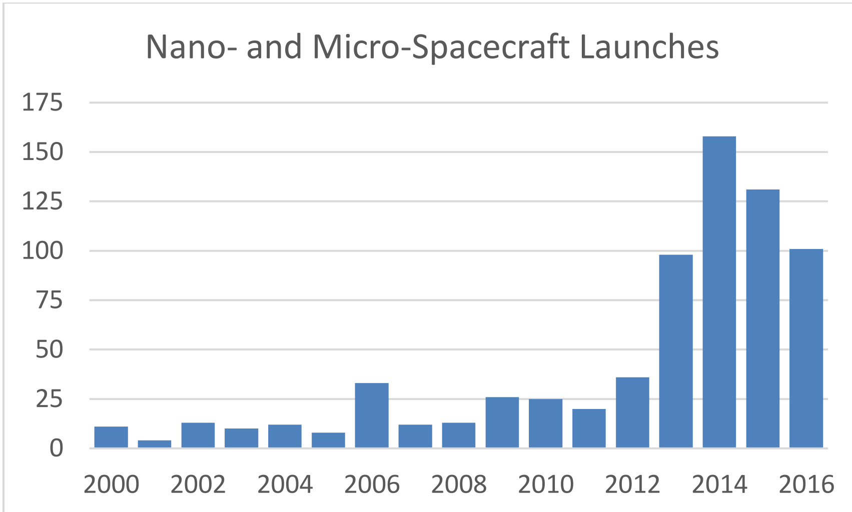


Figure 6 Annual nano- and micro-satellite launch rates

Programmatic Considerations

Early satellites may have been small due to the limited capabilities of early launch vehicles, and spacecraft masses generally increased to keep pace with the increasing payload mass capabilities of new launch vehicles. More options are now available to the spacecraft designer, and the choice to implement a project as a small spacecraft will consider factors such as mission objectives, available budgets, launch mass allocation, propellant/delta v mass fraction requirements, technology readiness, risk tolerance, and long-term programmatic organizational goals.

The key feature of small spacecraft – flight system affordability – can have fundamental impacts on several programmatic concerns. Cost estimation can be challenging, especially as new, standardized platforms change the scale and complexity of these satellites. The growing smallsat market has increased competition over scarce launch opportunities, causing prolonged launch delays. Finally, risk management approaches for smallsat missions may differ from those of much larger missions.

Cost

The introduction of standardized designs and a diverse set of COTS small spacecraft buses have lowered spacecraft development costs to a level accessible to most. Entry-level spacecraft development kits are priced below $10,000 US, and corresponding ground communications systems may be assembled from similarly priced components. Cost models, such as the Aerospace Corporation Small Spacecraft Cost Model (SSCM) provide cost estimation capabilities for mini and medium spacecraft projects but do not generally support cubesat cost estimation. (Eric Mahr, 2016)

The per-kilogram payload launch cost is often the driving factor in overall mission cost. For many years, this measure held steady at $100,000 per kilogram to Low Earth Orbit (LEO) and at least $225,000 per kilogram to lunar orbit. Ridesharing allows cubesat project to achieve launch costs of $30,000kg to $50,000/kg. As commercial access to space continues to grow, these costs are expected to decrease.

Launch Opportunities

Launch frequency can vary with the success of a launch vehicle product line. Typically, a government or commercial entity may seek a launch service provider that can launch every 3 months. High reliability launch vehicles – those that launch on schedule and successfully deliver their payloads – provide the best opportunity for all spaceflight projects, but typically at higher cost. Small spacecraft projects that seek lower-cost launch services may do so at increased risk of launch delays or launch failure, and ridesharing leaves secondary small satellite projects prone to delay when primary spacecraft issues force launch slips. A recent history of launch failures across many separate commercial launch service providers has reduced the overall smallsat launch rate.

The NASA CubeSat Launch Initiative (CSLI) was formed in 2008 to match cubesat projects with ride-share opportunities across the launch industry. CSLI subsidizes launches for non-profit, educational, and government organizations that could not otherwise acquire launch services. As illustrated in Figure 7, organizations across the U.S. have benefited from these CSLI-provided launch opportunities. Universities, high schools, and even an elementary school have flown science, technology, engineering and mathematics (STEM) cubesats that promote the education of the next generation of U.S. aerospace workers. (NASA, 2017)

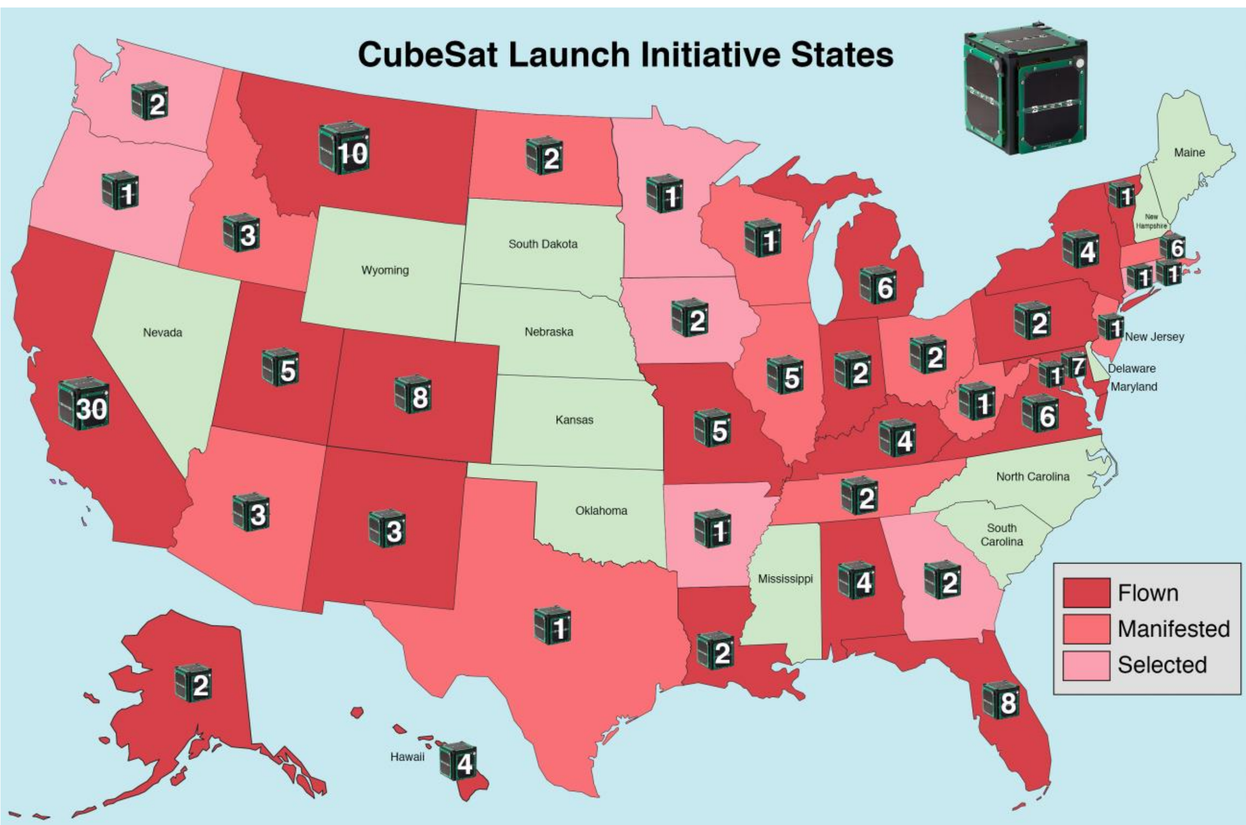


Figure 7 CubeSat Launch Initiative Recipients by State

Risk Management

The shorter schedules and lower development costs associated with small satellites can raise concerns of an increased mission failure likelihood, but small spacecraft projects can leverage cost effective risk mitigation strategies. Decreased complexity and use of heritage systems can mitigate the risks associated with the typically reduced testing and technical oversight investments in small spacecraft projects. At the same time, reliance on COTS parts, particularly in higher radiation environments, is a recognized risk area.

Even when higher failure likelihood remains, the overall risk (likelihood x consequence) may remain much smaller than the risks associated with larger spacecraft projects. The risk posture for a small spacecraft development should be determined during the proposal and/or formulation phase of the mission. Stakeholders must all be in agreement in order to maintain cost, schedule, and risk discipline.

NASA's methods for characterizing and managing risk are documented in NASA Procedural Requirements (NPR) 8705.4, *NASA Payload Risk Management*, in which all NASA spacecraft and instruments are considered payloads of launch systems or other carrier vehicles. Table 3 summarizes the document's risk classifications. For each class, NASA defines design, test, and mission assurance philosophies and provides further guidance in of areas that directly affect cost, schedule, and risk, such as single point failures (redundancy, Electrical, Electronic and Electromechanical (EEE) parts, test levels, etc.). Note that safety requirements do not vary between mission classes; these requirements cannot be waived or amended if it is proven that valid safety risk exists.

Characterization	Class A	Class B	Class C	Class D
Priority (Criticality to Agency Strategic Plan)	High priority	High priority	Medium priority	Low priority
National significance	Very high	High	Medium	Low to medium
Complexity	Very high to high	High to medium	Medium to low	Medium to low
Mission Lifetime (Primary Baseline Mission)	Long, > 5 years	Medium, 2-5 years	Short, < 2 years	Short, < 2 years
Cost	High	High to medium	Medium to low	Low
Launch Constraints	Critical	Medium	Few	Few to none
In-Flight Maintenance	N/A	Not feasible or Difficult	Maybe feasible	May be feasible and planned
Alternative Research Opportunities or Re-flight Opportunities	No alternative or re-flight opportunities	Few or no alternative or re-flight opportunities	Some or few alternative or re-flight opportunities	Significant alternative or re-flight opportunities
Examples	HST, Cassini, JIMO, JWST	MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads	ESSP, Explorer Payloads, MIDEX, ISS complex subrack payloads	SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX

Table 3 NASA Payload Risk Classification

Class A missions are the most costly given the requirements levied on the project for mission success. As the least costly, and presumably lower priority, missions, Class D missions are assigned less stringent requirements. Small spacecraft are typically defined as Class C or Class D missions. It is typically assumed that Class D missions are "higher risk" as compared to Class A missions, However, there is a lower inherent consequence of Class D mission failures, given their low priority, significance, and investment level (e.g., development cost). Thus, the total risk (consequence x likelihood) of mission failure may be no higher than that of an average spacecraft.

Small satellite development strategies that can achieve reasonable costs while supporting mission success include:

- Capability driven (design-to-cost) approaches rather than the standard requirements driven approach
- Use of heritage hardware (build-to-print) and high technology readiness (TRL) solutions
- Applying large margins in the initial design phase to provide flexibility and parallel development (e.g., mass constraints can drive the design requirements of a spacecraft to a considerable extent—the need for optimizing a design will increase the cost of a development).
- Verification by test rather than reliance on increasing analysis sophistication
- Choosing the level of integration for verification based on function criticality
- Use of modular, layered architectures
- Standardized interface, components, and software for multi-use satellite bus developments
- Reduction of radiation-induced parts failure likelihood through limiting mission lifetime or the added shielding
- Use of redundant spacecraft – such as cubesat swarms – rather than through redundant subsystems to achieve reliability goals.

Additional discussion of similar low-cost development strategies may be found in the RAND Corporation's 1998 report "The Cosmos on a Shoestring".

Because it is one of the most important drivers of both risk and cost, complexity is an important variable to attend to in development of low-cost, small spacecraft. Methods to reduce complexity include:

- Careful reuse of software
- Minimized use of pyrotechnics and complex mechanical systems
- Separation of critical functions to prevent cascade failures
- Streamlined organizational interfaces and communication
- Use of a small, focused core team throughout the project (e.g., avoid fractional FTE)
- Allowance for significant systems engineering resources

Systems engineering and mission assurance efforts are an important and cost-effective part of small spacecraft project risk management. Examination of typical costs distribution to subsystems and processes in a spacecraft development in Figure 8 shows that systems engineering (~4% of total) and mission assurance (~2%) costs are not large portions of the overall cost. However, they are critically important to assuring success of a mission. Cost cutting in these areas saves little and can significantly increase the probability of failure.

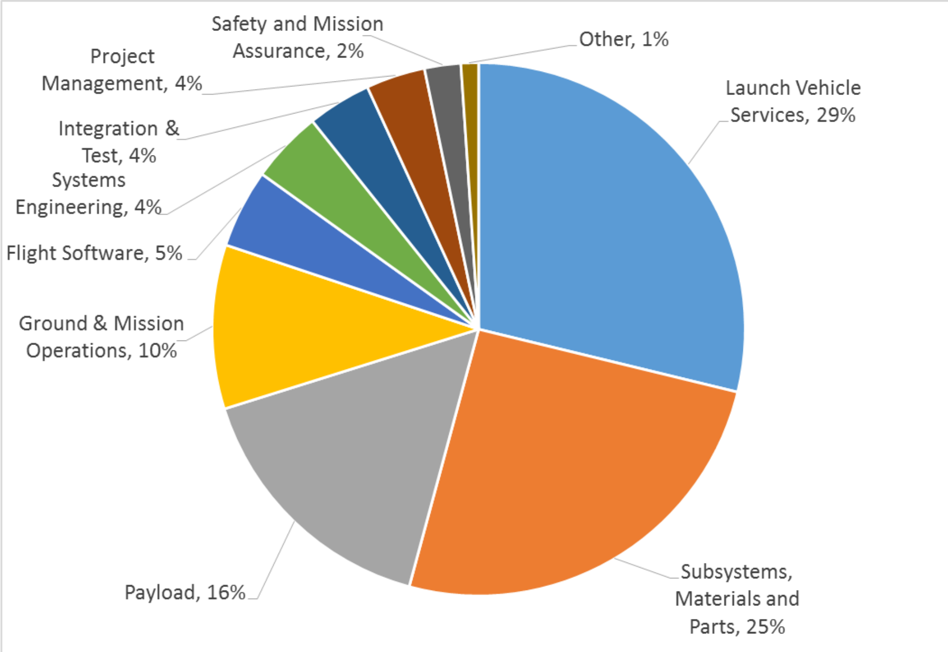


Figure 8 Example Small Spacecraft Costs by Category

Life Cycle Considerations

Small satellite development and operation involve the same activities and phases that are associated with larger spacecraft.

Integration and Test

Integration and Test of spacecraft is an essential process for small spacecraft builders seeking to reduce the risk of failure in during launch and operation. An understanding of how to tailor testing approaches for each application is key to keeping testing costs to a minimum. A logical testing flow, including adequate configuration management process of documents and hardware, is also necessary to make sure test costs are not unnecessarily increased. It is important not to under-test or over-test a spacecraft. Guiding test documents already adopted in the industry such as Goddard Environmental and Verification Specification (GEVS) have been written with past lessons learned in mind. Shock, vibration, acoustic, Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC), thermal vacuum, and other general environmental stress screening tests are common for small spacecraft.

A qualification and acceptance program is considerably more costly but allows for design modifications if a design flaw is found in the qualification model. Qualification systems are tested with higher loads to ensure a flight system should predictably pass an acceptance test once fully integrated based up the qualification unit. This is due to the higher margin factors placed on qualification unit vs acceptance units. Design flaws are usually witnessed in the higher stressed qualification program eliminating significant risk that the flight unit will experience failure in acceptance level stressing conditions. Proto-flight approaches condense the schedule taking more risk that only one article with be tested at higher loads but assumes more risk for failure on the flight article.

Test programs can add unnecessary risk if the system is over tested. It is not uncommon for a team to feel obligated to retest an entire system if a piece of the configuration is changed. Sending an entire spacecraft back for acceptance vibe retest may be a flawed approached if it originally passed its primary test. A calculated risk must be taken and weighed since retest may be more risky to the hardware than no test. Elimination of a simple subsystem vibe acceptance test in this case may spare potential harm to the overall spacecraft system.

Launch and Deployment

Historically, government-subsidized launches have been a main pathway for most of these secondary spacecraft. Recently, there has been a shift in LEO based missions with new commercial based launch opportunities. Four general categories of launch option exist for small satellites – dedicated launch, rideshare, hosting, and deferred deployment.

Mini and medium-spacecraft may use dedicated launch vehicles. The growing market for small spacecraft has spurred the development of a class of smaller launch vehicles that support small spacecraft needs. For example, IRIS and NuSTAR were both carried to orbit by Orbital ATK Pegasus XL launch vehicles that air-launch from carrier aircraft.

For smaller cubesats, launch and deployment opportunities typically leverage mass and volume margin from a larger mission's launch vehicle. Today, three launch options are available to cubesat customers.

Ridesharing arrangements provide an affordable meant for cubesats to "ride along" on and deploy directly from a launch vehicle. Often, cubesat deployers are mounted to the Evolved Expendable Launch Vehicle Secondary Payload Adapter (ESPA) ring that interfaces the launch vehicle to the primary payload. A typical configuration for such secondary payload mounting is shown in Figure 9**Error! Reference source not found.**. The Indian Space Research Organization Polar Satellite Launch Vehicle (PSLV) deployed a record 104 satellites – the 680 kg, medium-class CartoSat-2 mapping satellite and 103 nano-satellites. However, such secondary payload launch opportunities have been limited and inconsistent over the last several years. 158 smallsats (1 to 50 Kg) were launched in 2014, 131 in 2015, and 101 in 2016. (Foust, Launch woes diminish demand for small satellites, 2017) This decline was due primarily to delays in launches caused by launch vehicle failures and other setbacks. Some of this pressure on ride shares may eventually be alleviated by the emergence of a new generation of dedicated small launch vehicles. Until then, the full advantage of fast development times for small satellites will be difficult to realize due to the challenge in securing timely, cost-effective launches.

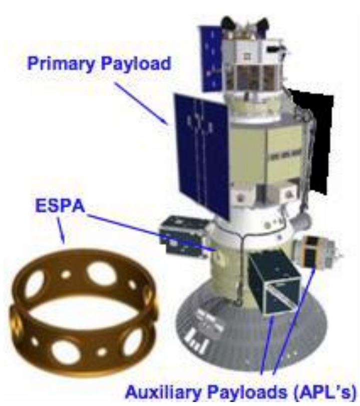


Figure 9 Cubesat secondary payloads installed on an ESPA ring

Cubesats may also be integrated into large satellites for deployment after the host spacecraft arrives on orbit. The 150 kg Fast, Affordable Science and Technology Satellite (FASTSAT), itself a mini-spacecraft launched from an ESPA ring, deployed the NanoSail-D cubesat after it separated from its launch vehicle. (Boudreaux, 2013)

Finally, cubesats may be ferried to an orbital platform (typically the International Space Station) for deployment at a later date. Commercial providers now offer services to transport cubesats to the ISS and deploy them. Figure 10**Error! Reference source not found.** illustrates a typical cubesat deployment from the ISS.

Figure 10 Cubesat deployment from ISS (NanoRacks)

By whatever means, launch generally represents the most severe vibrational and shock environment for the spacecraft and the greatest opportunity for spacecraft mechanical failure. The duration and levels will vary, but NASA's General Environmental Verification Specification (GEVS) provides a comprehensive approach for testing to the anticipated environments for most available launch vehicles. Launch phase durations can vary in the number of minutes but in general, most LEO launches are around approximately 10 minutes in duration. Differences in Thermal Coefficient of Expansion (TCE) between dissimilar materials can also lead to failure after repeated thermal cycles or even after just one major change in thermal conditions (rate dependent in some cases)

Small spacecraft may be launched powered on or powered off. There are advantages to both approaches, but launch costs are typically lower for a spacecraft that is launched powered off. Launching powered on brings additional safety considerations—additional, redundant inhibits are needed to prevent premature initiation of propulsion systems, for instance.

Small spacecraft deployment may be accomplished through several means. Most common for Cubesats is with a dispenser in which a door is opened and a spring pusher foot ejects that spacecraft. For non-cubesat small spacecraft, ESPA rings and Payload Adapter systems are used with spring load separation systems. After deployment a spacecraft will immediately begin a safe mode routine after powering up or if already powered, the spacecraft will typically begin a detumbling routine and start working through a sequence of GN&C events with a ground based mission operations team.

Ground Data Systems and Operations

Ground data systems should be designed/built in parallel with the spacecraft. Requirements for supporting ground data systems can vary based on spacecraft complexity, mission complexity, and destination. Complex spacecraft and missions may demand near-continuous communication with ground support functions. This generally necessitates the use of multiple ground-based communications terminals provided by communications networks such as the Near Earth Network (NEN). Simpler missions that only require brief daily or less frequent communications sessions may use single ground stations.

Small spacecraft with deep space destinations (lunar orbit or beyond) may require use of Deep Space Network communications assets, while earth orbiting small spacecraft may use a range of communications options from the Near Earth Network to single independent ground stations. Multiple universities have developed and fielded such ground stations, and turnkey COTS ground station systems are marketed as solutions for cubesat developers.

Mission Operations can take many forms, as dictated by the same needs that define ground data system requirements. Complex spacecraft and missions may require larger operations teams and continuous uplink of command sequences, while simple and / or highly automated spacecraft may require little more that periodic data transfer and simple monitoring. In general, mission operations teams are sized and trained to support at least once-a-day communications sessions.

Decommissioning

Another area of concern for small satellites, particularly cubesats and their constellations, is their potential contribution to orbital debris. Depending on which orbit they travel to by way of rideshare, cubesats could be in orbit from months to up to 25 years. If spacecraft are in orbits that will exceed 25 years, then deorbit systems must be used. There have been advancements in drag based systems that deploy and increase drag to meet these requirements. Other methods require propulsion systems to lower the orbit—these are often mass, volume and cost prohibitive. Without specific requirements and corresponding solutions for deorbiting, very small spacecraft may contribute to debris hazard for years and the problem could exponentially increase as space-based commercial industry grows.

Small Spacecraft Technologies

In general, small spacecraft must provide the same, albeit appropriately proportioned, functional capabilities as any spacecraft. Smallsat lifetime and level of subsystem redundancy, however, are typically more limited than those of larger spacecraft. Mass and volume constraints significantly affect tend to limit power, propulsion, and communication subsystem performance. These constraints, combined with typically low project budgets, encourage innovative solutions. The use of commercial off the shelf (COTS) technologies and components from other industries in small satellites has become increasingly common as a means to simplify system development efforts and achieve the low cost goals typical of such projects.

While early smallsat development involved the creation of new and unique spacecraft bus designs, more recent smallsat projects have successfully leveraged a growing number of off-the-shelf bus designs. The increasing quantity and variety of small spacecraft leverages a growing availability of commercial and open standards. Commercial smallsat buses, such as Orbital Sciences' LEOSat-2, Surrey Satellite Technology Ltd.'s SSTL-70, Millennium Space Systems' Altair, and Sierra Nevada Corporation's SN-100, allow development of mini satellites. Commercially-produced kitssimplify the development and integration for academic spacecraft projects. Use of other COTS technologies and components can enable faster, lower cost development of novel cubesat architectures. For example, NASA's PhoneSat leveraged a commercial smartphone as the spacecraft command data handler.

Deployable structures, although common in all spacecraft classes, can be particularly important in small spacecraft. Such structures allow smallsats to achieve much larger dimensions to support power generation, communications, and instrument needs. The NuSTAR spacecraft, shown in Figure 11, deployed 10 m mast structure to accomplish on-orbit assembly of an X-ray telescope. The Dellingr spacecraft will similarly deploy magnetometers on the folded boom structure shown in Figure 12. These techniques allow small launch packages to become much larger scientific instruments. Other novel mechanical designs hold promise to provide larger support structures for solar arrays, communications antennae, and other key components for future small spacecraft.

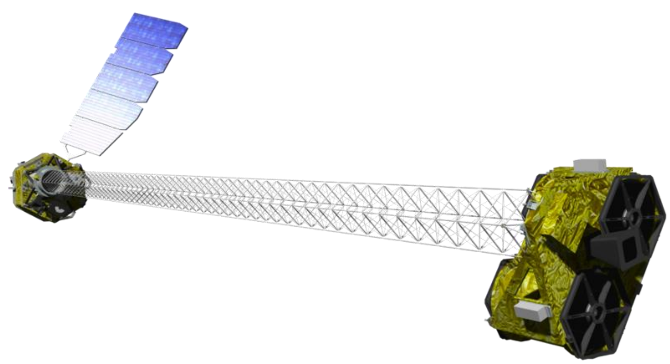


Figure 11 NuSTAR in deployed configuration

Figure 12 Dellingr spacecraft with magnetometer boom and antennae extended

Small spacecraft electrical power systems typically rely on photovoltaic solar cells and Lithium batteries to generate and store energy. While low-cost single junction photovoltaic cells may be used for very low power spacecraft, most small spacecraft designs leverage space-rated, high-efficiency triple junction photovoltaic cells. Early cubesats integrated flush-mounted solar arrays into the spacecraft sides, but increased power needs have inspired novel designs for larger deployable solar arrays. While traditional, single-axis hinge mechanisms allow the deployment of cubesat solar array “wings”, newer mechanisms employ multi-hinged umbrella-style solar arrays.

Traditionally, small spacecraft have employed chemical mono- or bi-propellant propulsion systems for recurring tasks such as primary trajectory maneuvers, trajectory correction maneuvers, attitude maneuvers, and momentum management (such as “momentum dumping” used to manage reaction wheels). Such systems, however, are typically complex and demand significant fractions of overall spacecraft mass and volume. Traditional chemical propulsion systems also introduce safety concerns. Cold gas propulsion systems offer simpler, and generally safer, design alternatives. The low mass of small spacecraft can make electric propulsion techniques, including Hall effect thrusters, plasma thrusters, and ion propulsion systems, reasonable alternatives. NASA’s iSat mission will demonstrate practical use of an Iodine Hall thruster to maneuver a cubesat in low Earth orbit. (John W. Dankanich, 2014) Solar sail propulsion technologies may prove to be viable for cubesats as well. The 6U Lunar Flashlight and Near Earth Asteroid Scout (NEA-Scout) spacecraft shown in Figure 13 will each deploy 9 m x 9 m solar sails to provide propulsion. (Castillo-Rogez, 2014)

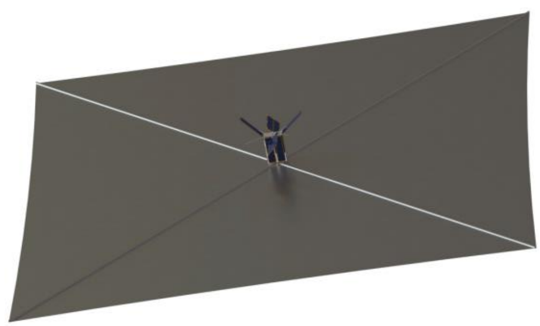


Figure 13 Solar Sail Configuration for Lunar Flashlight and NEA Scout spacecraft

Like larger spacecraft, smallsat Guidance, Navigation, and Control (GNC) subsystems may employ star trackers, reaction wheels, sun sensors, Earth limb sensors, inertial measurement units, torque coils, torque rods, Global Positioning System (GPS) receivers, and gyroscopes as GNC sensors and effectors driven by software- and/or hardware-driven control systems. Key drivers in GNC performance are antenna pointing accuracy requirements, payload pointing, and attitude restrictions defined by thermal environment constraints. Many LEO cubesats require only general pointing, on the order of ±1 degree, to adequately point solar arrays toward the sun and antennae toward communications terminals. For these systems, hysteresis rods and permanent magnets that interact with the Earth’s magnetic field may be adequate. Cubesats with such passive attitude control are ideal for achieving pristine microgravity environments in LEO for genetic based experiment. Beyond LEO, however, active attitude control is necessary due to the absence of a magnetic field.

Thermal control system implementation options for small spacecraft are limited due to mass and power constraints. Passive thermal control methods such as Multi-Layered Insulation (MLI), surface coating (coatings, paints, and tape), heat pipes, and conductive thermal pathways/straps, provide low-cost and low-mass options that are particularly attractive in pico- and nanosat applications. Active cooling mechanisms, such as electrical patch heaters, Thermo-Electric Coolers (TECs), and pump-driven liquid thermal conditioning loops, provide greater control over the spacecraft’s internal thermal environment at the cost of additional complexity, higher spacecraft mass, and increased electrical power requirements. Recent demonstrations indicate that use of a pressurized bus container can bound temperature extremes experienced by spacecraft avionics, thereby reducing the necessary thermal system design effort and reducing development cost.

Small spacecraft communication systems have employed at least 25 Radio Frequency (RF) bands including VHF, UHF, L-Band, S-Band, X-Band, and Ka bands. (NASA perspectives on Cubesats and Highlighted Activities, 2015) The recent development of software-defined radios, in which a radio can be tuned to specific frequency throughout a dynamic range using software commanding, has introduced new options for smallsat communications. Smallsats may use patch, whip, evolvable (computer-generated using genetic algorithms), parabolic reflector, or deployable antennas. Laser-based optical communications systems with very high data transfer rates will likely play an important role in future missions, but cubesat mass, power, and volume constraints will likely limit performance on these platforms.

Small spacecraft command and data handling (CDH) designs typically trade high processor performance for low mass, low power, and robustness. Additionally, the need to control costs tend to drive small spacecraft projects to use COTS components and interface standards. For example, COTS processors (such as the BAE systems' RAD-750 radiation hardened single board processor) and standard interfaces such as the serial bus, universal serial bus (USB), and I^2C protocols have been used in small spacecraft. Satellites flown within the Van Allen Belts (commonly low earth orbit missions) are subject to a comparatively benign radiation environment. Satellites flown through or beyond the 60,000 km edge of the Van Allen belts, however, experience much higher radiation doses and require design features – either radiation hardening or radiation shielding – to handle this exposure.

Radiation hardening entails designing an electronic chip with radiation dosing as a driving requirement. The primary objective of radiation hardening is to ensure the performance of device operates as intended and extends the useful life of the device while experiencing radiation and post radiation dosing. In space a number of radiation pathways may be incident upon an electronic device while in, passing through, and travel beyond Earth's radiation belts/magnetosphere. Material selection and physical design of gate geometry of solid state electronics can be a key factor. In some cases, larger electronic gate sizes are preferred in radiation environments as they provide greater reliability over newer, smaller gate designs. Electronics with slow performance and high reliability often are chosen over processing speed. For missions requiring radiation hardening, processing speed may be traded for overall functional reliability. When the cost of radiation hardened parts is too high, some missions turn to alternate systems architectures utilizing items such as "watch dog" timer functions that recover from processor latch-ups before such events become total permanent failures.

Radiation shielding may be used to protect devices not inherently radiation hardened. A design can mitigate the amount of radiation that reaches electronic circuitry by way of layering radiation materials that have an effective Linear Energy Transfer stopping characteristic. Heavy materials such as lead are effective in stopping radiation transmission but are often too heavy for use in small spacecraft. Instead, a clever layering of lighter materials, each with good Linear Energy Transfer stopping characteristics, can provide effective shielding.

Case Studies

Several recent NASA projects demonstrate emerging trends in smallsat development. The GeneSat-1 mission represents NASA first use of a cubesat for astrobiology research. The COTSAT spacecraft illustrates a novel design approach to simplify spacecraft design, and the LADEE mission illustrates the use of a mini-satellite bus to execute planetary exploration.

GeneSat-1

GeneSat-1, NASA's first cubesat satellite, was a joint effort involving NASA Ames Research Center, Santa Clara University, California Polytechnic University at San Luis Obispo, and Stanford University. This spacecraft launched successfully in December 2006 on a Minontaur-1 Launch Vehicle as a rideshare with the TacSat-2 Mission.

NASA leveraged high reliability, radiation tolerant, low power electronics, coupled with the recent introduction of high efficiency triple junction solar cell technology, to advance cubesat Technology Readiness Levels (TRLs). The 3U spacecraft bus, illustrated in Figure 14, consumed an average of just 3-5 watts and a peak of 5 watts – a feat enabled by both clever system engineering, recent improvements in microprocessor technologies, and the identification of low cost COTS communication technologies that were compatible with the space environment. Despite its low power consumption, GeneSat-1 operated its biological experiments within a benign payload temperature of 27 ± 0.5 degree C.

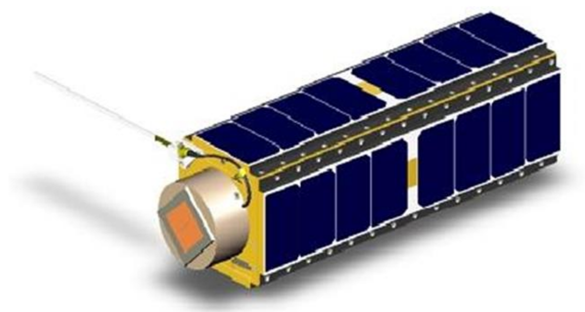


Figure 14 GeneSat-1

Given the minimal technology investment associated with cubesat development, COTS parts are used extensively and the predicted probability of flawless on-orbit operation was considered low. To ensure that GeneSat-1 would not negatively impact the primary mission, the required mechanical integrity and reliability of the cubesat system and its dispenser were considered to be very high. This approach is now known at the secondary payload "do no harm campaign approach". Many of the early cubesat such as GeneSat-1 had very large structural margins added to ensure the mechanical integrity of the system would never be a concern. This system was intentionally overdesigned for mechanical strength to alleviate concerns of structural failure damaging a neighboring environment on the launch system. The team tested the system to strict NASA mechanical environmental testing requirements and proved the system could not negatively impact TacSat-2's success.

Cost Optimized Test of Spacecraft Avionics and Technologies (COTSAT)

NASA Ames Research Center developed the 250 kg Cost Optimized Test of Spacecraft Avionics and Technologies (COTSAT-1) as a rapid prototype, low-cost spacecraft for science experiments and technology demonstration. COTSAT-1 demonstrated significant spacecraft design cost reduction through methods and technologies that maximized reuse of previously developed spacecraft hardware, software and related technology on future missions. The spacecraft platform, shown in Figure 15, was designed to accommodate low cost access to space for various remote-sensing payloads while allowing future expansion for potential biological payloads. Though much larger in mass and volume than a cubesat, COTSAT used similar philosophies in COTS parts selection and low cost targets. The system's size enabled it to carry, for a similar cost, a range of payload sizes beyond that possible using the Cubesats standard.

COTSAT-1 leveraged the use of the one atmosphere pressurized structure to house spacecraft components, a design feature similar to that previously used in Soviet and Russian spacecraft. This artificial environment makes it feasible to incorporate a wide array of pre-built hardware, including Commercial off the Shelf

(COTS), Modified off the Shelf (MOTS) and Government off the Shelf (GOTS) hardware. Hybridizing a one-atmosphere pressure vessel with current COTS technologies provides a significant subsystem cost reduction, in most cases, by orders of magnitude by elimination of many of the space hardening steps that would be needed for hardware directly exposed to space vacuum. By using COTS hardware, the spacecraft program can utilize technology investments already made by commercial vendors. (Swank, 2009)

Figure 15 COTSAT

COTSAT-1 also incorporated industry data interface standards such as USB 2.0 and Ethernet to reduce development and integration time. Where inexpensive COTS hardware solutions are not readily available, subsystems are designed and developed in-house. This includes reaction wheels, star tracker and electrical power systems. The one atmosphere avionics bus structure encases a PC-104 CDH and a custom Electrical Power System. The COTSAT-1 project used open source software, including GNU/Linux and existing software libraries and device drivers to reduce software development and integration time.

Beyond LEO, radiation exposure still remains a challenge for this platform although programs in low cost shielding are underway and NASA has a solution to this issue in development. This means a system of this low cost could also be a candidate for a new class of spacecraft that is low cost for travel beyond the Van Allen Belts. Resolution of radiation limitations in commercial electronics would pave the way for future low cost exploration platforms beyond low earth orbit.

Commercial organizations have begun licensing COTSAT patents, bringing the derived technologies to the marketplace and into service in low Earth orbit. (Hera Systems, Inc., 2015)

Lunar Atmospheric Dust Environment Explorer (LADEE)

Another example of Low Cost approach to building deep space vehicle was demonstrated successfully on the LADEE Mission. The LADEE spacecraft, shown in Figure 16, was designed, developed and integrated at NASA Ames research Center for a cost of $282 Million (including the launch vehicle). The LADEE system was 383kg system when fully fueled. The mission included three science instruments (Neutral Mass Spectrometer-NMS, Ultraviolet Spectrometer –UVS, and Lunar Dust Experiment-LDEX), to characterize the exosphere of the Moon while in a low altitude retrograde elliptical orbit. The spacecraft also carried the Lunar Laser Communications Demonstration (LLCD) payload, the first demonstration of earth—to-space laser communication.

Figure 16 LADEE

Many of the systems used on LADEE were COTS or modified COTS. LADEE launched on a Minotaur V rocket on September 6, 2013 and successfully performed its mission requirements in addition to a technology breakthrough with the successful demonstration of a Laser Communications system achieving a 622 Mbps data transmission rate from lunar orbit to an Earth base ground receiving station.

Conclusion

Small spacecraft support a broad spectrum of needs in space exploration and commercialization. From their humble beginnings of early spaceflight, the opportunities and available options for the application of small satellite technologies makes spaceflight more accessible to government, commercial, and academic institutions. Today, the key challenge in expanding the small spacecraft market is the provision of sufficient affordable launch opportunities.

As humankind's brief space history has shown, small spacecraft platforms will continue to serve an important role in space exploration. They likely will be the genesis and proving ground for future space technology advancements. They also will continue to serve as the training ground for future space innovators and as a stepping stone leading to large spacecraft flagship exploration missions. One can only wonder what the seed of small spacecraft technology development will yield in the future.

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